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An Experimental study of Coupling between Combustor Pressure, Fuel/Air Mixing, and the Flame

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Abstract

Fuel-air mixing behavior under the influence of imposed acoustic oscillations has been studied by investigating the response of the fuel mixture fraction field. The distribution of local fuel mixture fraction inside the mixing zone, which is expected to evolve into the local equivalence ratio in the flame zone, is closely coupled to unstable and oscillatory flame behavior. As part of a series of works to study the combustion dynamics, an experiment was performed with an aerodynamically-stabilized non-premixed burner. Acoustic oscillations were imposed at 22, 27, 32, 37, and 55Hz. Phase-resolved acetone PLIF was used to image the flow field of both isothermal and reacting flow cases and this data along with the derived quantities of temporal and spatial unmixedness were employed for analysis. The behavior of the unmixedness factor is compared with the previous measurements of oscillations in the flame zone. This comparison suggests that local oscillations in fuel/air mixing are closely related to the oscillatory flame behavior. For each driving frequency, the mixture fractions oscillate at that frequency but with slight phase differences from the combustor pressure/flame intensity, indicating that the fuel mixture fraction oscillation are likely the major reason for oscillatory behaviors of this category of flames and combustor geometry.

Introduction

Combustion instabilities refer to the phenomena where the acoustic waves traveling inside the combustors get amplified in amplitude. This unstable burning results in undesirable effects on the combustor lifetime, and performance such as inhomogeneous burning of the fuel thus creating more pollutants, unacceptable level of vibrations and heat transfer rate possibly leading to the structural damages. Recently lean premixed combustion scheme has been employed for many industrial dump combustors for reducing pollutants (NOx), and increasing the fuel efficiency. But this scheme has an inherent tendency towards the combustion instabilities because the combustors are run very near the lean blow out limits.

Several research efforts have been devoted to the observation and measurements of this unstable pressure fluctuation, and also to the control of this phenomenon [1-4]. But mostly the efforts to actively control the combustion process have been case-specific. And there is a need for an extensive study of the mechanisms leading to combustion instabilities phenomena and the knowledge basis of general combustion dynamics occurring inside the combustors.

As an effort to establish a knowledge basis for designing combustors and a generalized methodology for actively controlling the combustion instabilities, it was suggested that we accurately measure the combustion dynamics such as the behaviors of flame and fuel/air mixing, and use these data in modeling and numerical estimations of combustion processes. Then when enough data has been collected over a reasonable range, and combustion response models based on these data are successfully developed, it is expected that a better understanding of combustion phenomena will be gained as well as a successful means to better estimations of the behaviors of newly developed combustors at design phases and control of combustion instabilities during the actual practical running phase.

As part of the research to this effect, oscillatory behavior of a non-premixed burner was studied by Pun et al. [5, 6]. This intended to study the dynamics of flame under acoustic oscillations, and revealed the phase-dependent responses of the combustion process under some frequencies (22-55Hz) of acoustic excitations. Current work is a study of the behavior of fuel/air mixing under the effects of forced acoustic oscillations of 22-55Hz, and is an extension of the work by Pun et al. [5, 6]. Figure 1 illustrates the region of interest for the previous and current measurements.

Lieuwen et al. [8] showed, theoretically, that the magnitude of the reaction rate and heat release oscillations produced by equivalence ratio perturbations increases significantly (by a factor of 5-100) as the equivalence ratio (unmixedness) decreases especially under leaner burning condition, while the effect of temperature died out and that of flow rate perturbation was conserved without being amplified. This implies that the equivalence ratio perturbations play a key role in driving the combustion instabilities in lean gas turbine engines.

Current work presents measurements of how the fuel/air mixing fluctuates in response to the imposed acoustic oscillations by means of phase-resolved acetone PLIF. Also by comparison with the previous measurements by Pun et al. [5, 6], it is to be examined briefly how the oscillatory behavior of flame is related to the mixture fraction oscillations by the acoustic oscillations imposed in terms of the phase differences in their oscillatory behaviors.

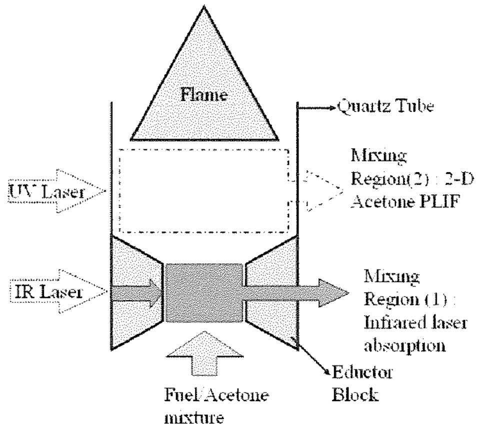

Figure 1. Region of interest; mixing is measured with acetone PLIF at region (2) in the mixing zone

Here, acetone [9-12] was seeded into the fuel stream and fully mixed with fuel before it enters the burner block so as to mark the fuel stream and PLIF technique was used to measure the distribution of fuel in the mixing region as shown in Figure 1.

Experimental Configuration

A schematic view of the acoustic chamber is shown in Figure 2. The acoustic chamber is made of an aluminum central section and a stainless steel top that houses the loudspeakers and allows direct exhaust of the product gases at the top. The exhaust port is unconstrained and is open to the atmosphere. At the bottom of the chamber, a circular section with radial vents allows air to enter but creates a closed-end acoustic condition. This section has two sets of inlet louvers cut on opposing sides to allow this radial airflow into the chamber, while maintaining acoustic closure. This creates a closed-end bottom and open-end top acoustic conditions. The loudspeakers housed in the upper portion of the chamber are used to generate the acoustic field. To protect the speakers from heat failure, they are attached to an air jet film cooling system. The loudspeakers are 12 inches in diameter and can handle 400 W (each) of continuous power. A 1000 W power amplifier along with a function generator provide the input signal and power to the speakers.

The burner, as shown in Figures 1 and 2, is a traditional jet-mixed type burner with flame anchoring occurring approximately in the middle of the quartz tube, with the exact height depending on the specific flow conditions such as fuel/air ratio. The fuel jet is 50% methane and 50% nitrogen and air is entrained and drawn into the jet as the flow moves through the eductor. The quartz tube is 5.72cm wide on each side and 11.43cm tall and is made of fused silica/quartz to enable observation and measurement of the flame.

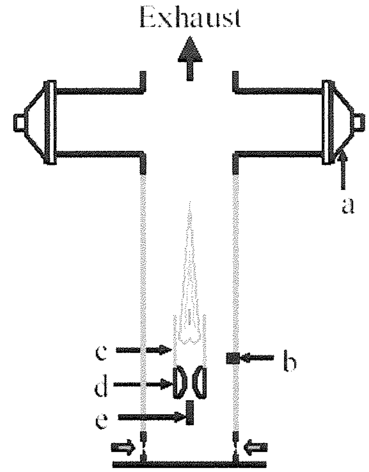

Figure 2. The combustion chamber: (a) loud speakers, (b) pressure transducer, (c) fused-silica burner tube, (d) eductor block (see Fig. 1), (e) fuel spud, arrows at the bottom indicate the air inlet.

Figure 3 is the layout of the acetone PLIF imaging system. An intensified CCD camera is used for the image acquisition, while a National Instrument data acquisition board (NI PCI 6014) along with pressure transducer (PCB 106B50) is used to measure and record the pressure and other signals. PLIF imaging of acetone is performed at the bottom portion of the quartz tube where no flame is present, as indicated in Figure 1.

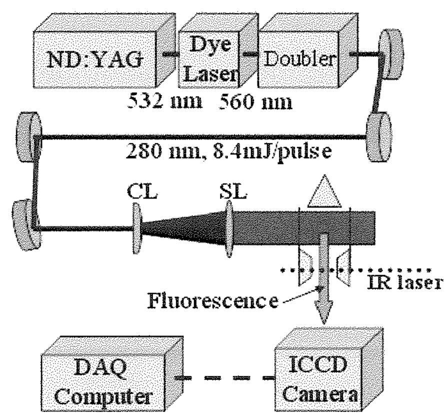

Figure 3. Schematics of the acetone PLIF.

The ND:YAG laser has internal laser frequency doubling and outputs a 2nd harmonic high power beam at 532 nm. This beam is used to pump a dye laser which operates at 560 nm. The output of the dye laser is, in turn, frequency doubled to 280 nm for excitation of acetone. The laser power entering the test section was 8.4 mJ/pulse, which is approximately 0.373 mJ/pulse/cm^2 of intensity.

The PLIF signal is captured on an intensified CCD camera with a maximum resolution of 512 by 512 pixels. An area of 5.5 by 4.1 cm is imaged onto 300 by 225 camera pixels. The PLIF signal passes through a UV high-pass filter which blocks all light lower than 300 nm in wavelength. This blocks laser beam scatter and passes the fluorescence signal which occurs mostly between 350 and 550 nm. Images are taken at random pressure phases, with the camera gating signal being recorded by the data acquisition system along with the pressure signal so as to enable appropriate post-processing. Post-processing involves sorting the images by the pressure phase, creating phase-averaged images, normalizing based on laser intensity.

Results

The global unmixedness is defined as

$$U_g = \frac{\sigma_g^{\ 2}}{(1-<x>_g)\cdot(<x>_g)}\ , \qquad (1)$$

where σ_g is the standard deviation and $<x>_g$ average of fuel concentration over the entire 2-D image, instead of one point with many measurements. The unmixedness is a normalization [13] of the variance σ_g^2 by the maximum possible value for the given $<x>_g$, evaluated by the variance of Housdorf relation, $\sigma_{max}^2 =<x>\cdot(1-<x>)$. When the fuel is completely mixed and homogeneously distributed, U is zero; when no mixing occurs, U is unity. A two-dimensional image collapses to a single value by this definition, which gives a quantitative measure of the magnitude of the variation of fuel/air mixing, the degree of fluctuation in fuel concentration over the entire region.

The local temporal unmixedness is defined as in the work by Fric [14],

$$U_t = \frac{\sigma_t^{\ 2}}{(1-<x>_t)\cdot(<x>_t)}, \qquad (2)$$

where σ_t is the standard deviation of the fuel concentrations drawn from repetitive measurements at the specific location over time, and $<x>_t$ is the time average of fuel concentration at that location. In respect to temporal unmixedness (U_t), higher values of U_t mean greater fluctuations in the fuel concentration. Thus, where U is larger can be interpreted as a region where more mixing occurs than in locations with lower values of unmixedness values. It is therefore expected that the high unmixedness region becomes wider down stream with the flow.

It is shown that high values of the temporal unmixedness occur in the shear mixing layer of the flow (30-75% from the center, see Fig 4). There is not much variation between cases at different excitation frequencies, but they show clear position-wise dependency. In figure 4, lighter shading indicates a region with a higher value of unmixedness, thus marking a region of high fuel concentration fluctuation. Further downstream from the eductor block (upward in Figure 4), the shear mixing zone widens as expected. The low temporal unmixedness in the core region, of 0 – 30 % distance from the center, is due to the high, and relatively uniform, fuel concentration. This shows the core region is still fuel dominant and needs further mixing Here, the dark region outside the shear mixing layer is largely due to homogeneously low fuel concentration.

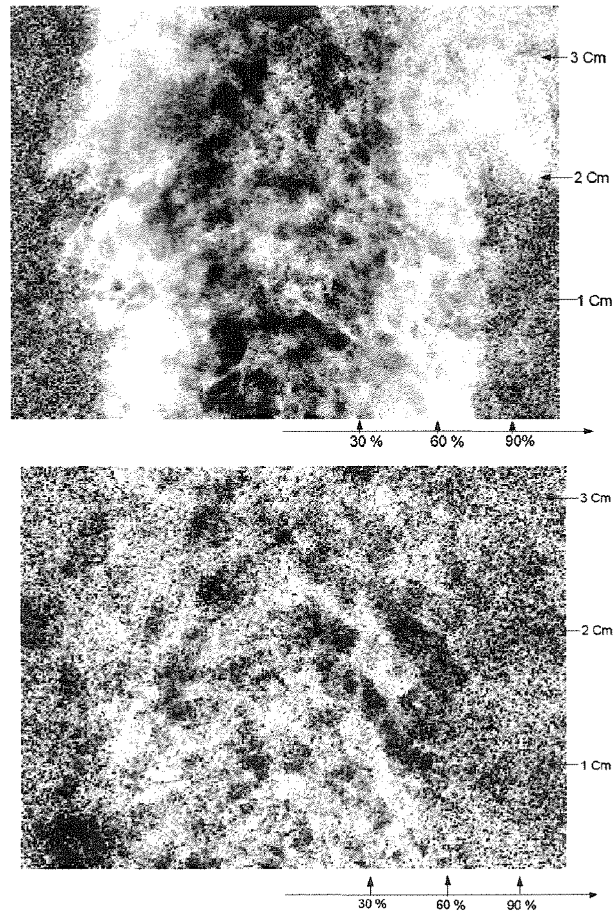

Figure 4. Two-dimensional maps (adjusted) of temporal unmixedness at 37Hz, (top) reacting and (bottom) non-reacting cases.

In the reacting case, due to the turbulent flow field generated by the heat release from the combustion processes, the unmixedness values in general are much higher than those in the cold flow as well as in the buoyancy driven flow structure in the reacting case. The reacting cases have a flow with significant post-reaction buoyancy, creating an enhanced vertical velocity component. This means that for the same vertical location, the reacting flow cases will resemble lower vertical locations (earlier times) in the non-reacting cases. This is evidenced by the fact that the non-reacting cases are mostly mixed by the time the flow reaches the imaging area while the reacting flows are still undergoing mixing (Figure 4). Direct comparison of mixing processes with and without combustion in this work is a rare observation.

Figure 5 is a 3D plot of the power density spectrum [7]: radial location vs. the Fourier transform of the time series data at each location vs. intensity of each frequency at each radial location. This particular plot is for a 32 Hz driven frequency and reacting flow, and shows that there is a very strong peak in the mixture fraction oscillations in response to an imposed acoustic field. This spike is not only narrow in frequency, but also matches the driving frequency as the frequency was varied from 22 to 55 Hz. The spike was between 2 and 3 orders of magnitude stronger than the natural, low frequency oscillations that are present. This clearly demonstrates that the acoustic oscillations cause oscillations in the fuel mixture fraction in the pre-flame zone at each driving frequency and, that there is a strong complex coupling between flame oscillations, and the resulting acoustic field.

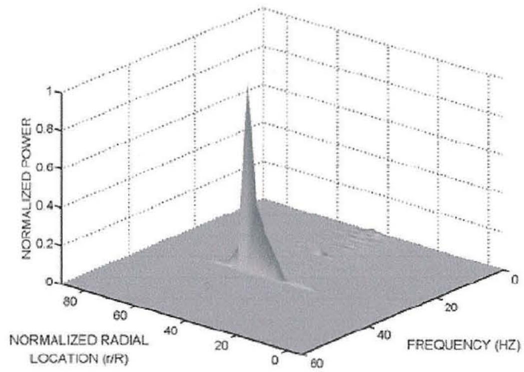

Figure 5. Power density spectrum for 32Hz, reacting flow [7]

Also, since no strong frequency preference is seen in the outer portion of the flow, it is most likely that the coupling is not a strong function of the vortex shedding from the fuel tube exit.

The phase dependence of the mixing behavior is shown in Figures 6 and 7. The role of combustion processes in causing higher uncertainties in fuel/air mixing is observed from the comparison with the non-reacting case (blue, in Figure 6), where the only difference is the presence of flame.

The global unmixedness is presented versus the excitation frequency and the phase during a cycle of excitation at each frequency in Figure 6. Greater values in global unmixedness factor, the degree of inhomogeneous mixing in the region, is observed in the presence of flame, and the mixing at higher frequencies (32-55Hz) is much more affected by the presence of the flame than at lower frequencies (22, 27Hz). The combustion process alone causes huge differences in mixing with increase in the unmixedness value up to a factor of 4. The increase in unmixedness with frequency for the reacting flow case seems to be caused by the interaction between the combustion process and the acoustic excitation, and it seems more plausible when compared to the non-reacting case where the tendency is actually in the opposite direction. While the effect of combustion process has a great effect on the behavior of mixing, mixing is affected by the phase of excitation as well.

Figure 7 shows the oscillatory behavior of mixing at some selected frequencies of 27 and 37 Hz, with and without the flame. The sine waves in bold lines correspond to the acoustic waves imposed. Pressure waves represented in sine waves are used as the reference for determining the phase of the data collected. The measured oscillatory behaviors of mixing are shown with the approximate sine waves corresponding to the first mode of unmixedness oscillations (blue lines). Examining qualitatively and trend-wisely, the degree of mixing (unmixedness) oscillates at the driving frequency (Figure 5) with some phase differences though there's a slight difference in phase and magnitude in mixing oscillations.

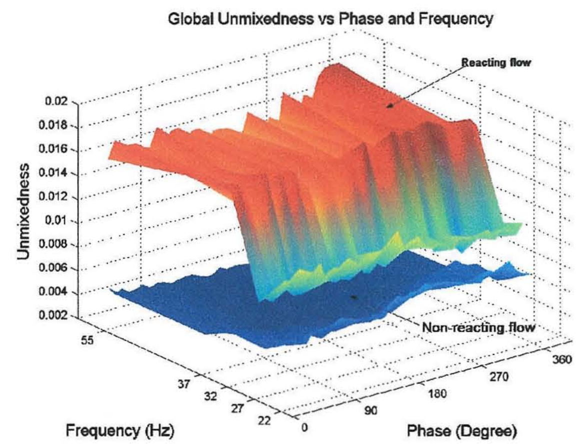

Figure 6. 3-D representation of global unmixedness vs. excitation frequency and phase.

Measurements show quite clearly that the behaviors of mixing are oscillatory at the driving frequencies. This figure strongly suggests that the oscillations of mixing is caused by the acoustic waves inside the combustor and is responsible for or at least closely related to the oscillatory behavior of flame to a certain degree. Accepting the reasoning by Lieuwen et al. [8] that the oscillations in local mixing cause oscillatory behaviors of flame burning and even worsen them, it can be also said that one of the major causes leading to unstable burning, the oscillations in fuel/air mixing, is measured and presented to be seen here. However, in this work, there is a clear limitation in supporting or directly relating to Lieuwen et al.'s work in that the oscillatory fuel/air mixing is not the input variable that could be modulated as in Lieuwen et al.'s work [8] but another output as a function of imposed acoustic excitation just as the flame behavior.

It is shown, in Figure 8, that the phase differences between reacting and non-reacting flow cases exist. But these phase differences increase in the same way the flame oscillatory behavior does. When the differences in phase between the behavior and mixing and the oscillatory flame behavior are examined, especially at frequencies 27-55Hz, reacting flow case only, it seems that the phase difference is kept quite consistent with around 100-120 degrees behind or, 240-260 degrees ahead. Here, in the right hand side of Figure 8, non-reacting flow case (blue line) is also shown for comparison with the reacting case, not with the flame oscillations. Currently it is hard to reason how the phase differences are relating the behaviors of fuel/air mixing and the flame due to the narrow frequency range, but from the

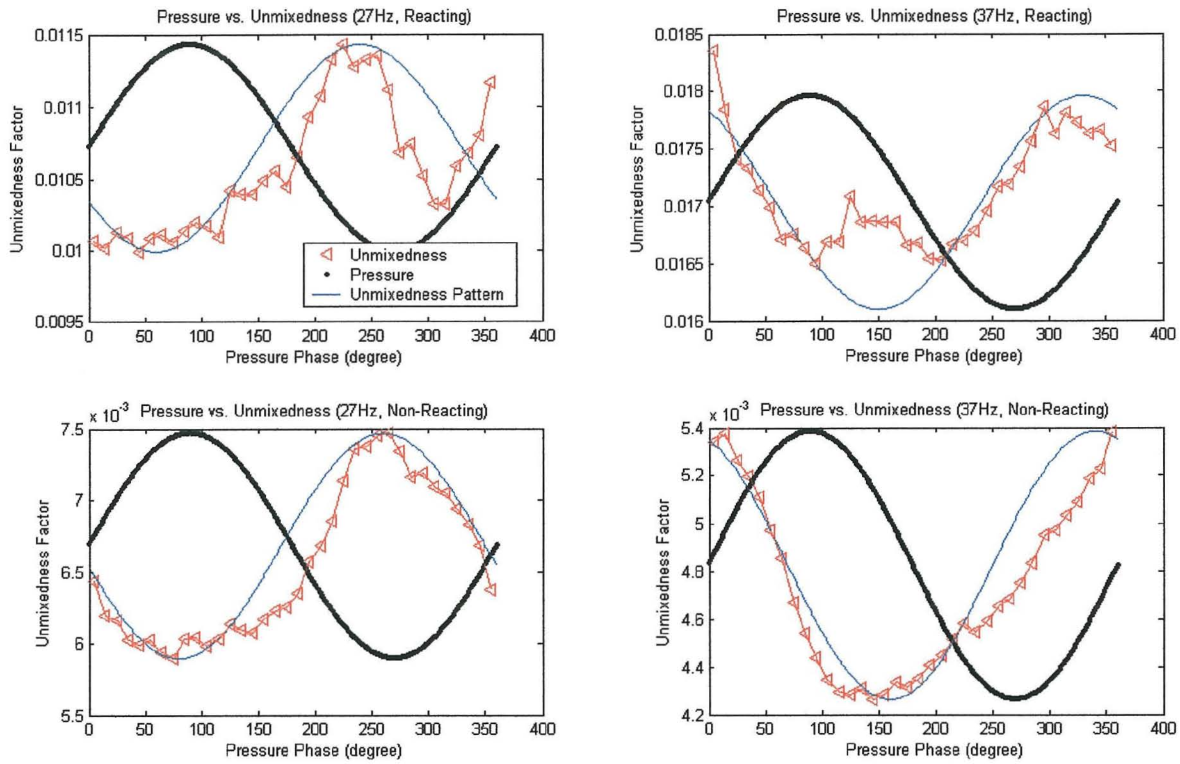

Figure 7. Oscillatory behaviors of global mixing presented with reference acoustic wave (dark sine wave). Thin blue lines indicate the approximation of mixing behavior to phase-shifted sine waves.

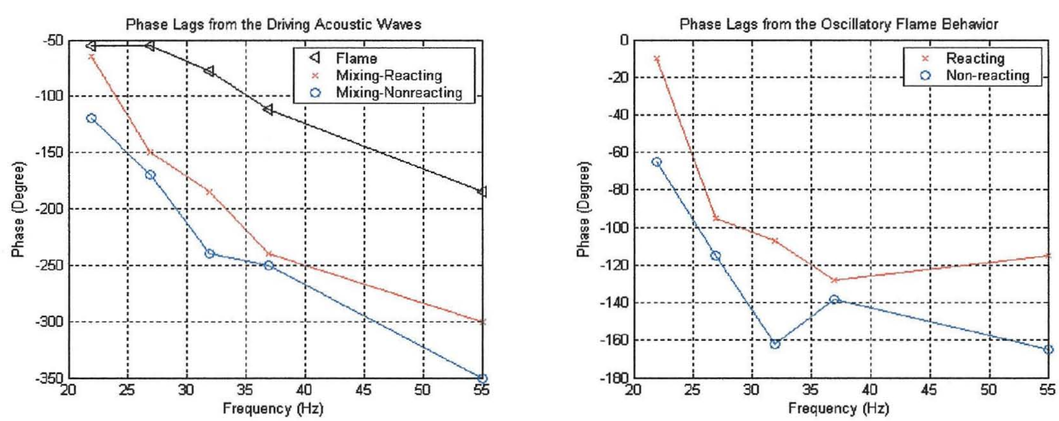

Figure 8. Comparison of phase shifts of mixing and flame [5, 6] behaviors. Phase shift from the driving acoustic wave (left); from the oscillations in flame (right)

trend shown by the phase differences, it can be said that the flame and mixing behave influencing each other. To make a conclusive statement, however, more research is required in higher frequency region. And also analysis based on chemical time scale (flame burning) and diffusion time scale to according to the jet speed will be helpful in explaining these phase differences.

Conclusion

Mixing is a significant factor in causing unstable combustion, and our work here experimentally showed that the root of this phenomenon – the onset of unstable burning due to the oscillations in mixing – can be caused by acoustic oscillations inside combustors

According to the results presented, there exists a strong coupling between mixing and the acoustic field imposed. It is also evident that the two-dimensional temporal unmixedness distribution map gives information about how fuel/air mixing is structured in the mixing region, and where the fluctuations in temporal unmixedness are strongest.

It is clear that the acoustic forcing causes a strong periodicity in the mixing layer at the driven frequency. In this work, the effects of the oscillations in mixing (unmixedness) and mass flow rate could not be decoupled due to the inherent experimental limitations. Still, the acoustic waves made oscillations in the overall mixing of fuel and air, and it was experimentally confirmed in the frequency region of 22-55 Hz.

The presence of a flame intensifies the distributions of uncertainties in the mixing zone, in terms of temporal unmixedness, more structured than those in the non-reacting cases. Not only the imposed acoustic waves, but also the heat released and buoyancy produced by the combustion process, play important roles.

Acknowledgements

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